

Variations in the Lava of the 1959 Eruption in Kilauea Iki¹

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IN RECENT YEARS the Hawaiian Islands have become of great importance in studies concerned with igneous petrogenic theory. This is partly because of the total absence in that region of sialic crust that might affect the formation of other rock types by its assimilation in rising magma. Partly, also, it is because of the extensive lateral and vertical exposure of successions of rocks, the structural and stratigraphic relationships of which are now well known. These conditions have attracted to the area workers from many parts of the world, and progress in knowledge of Hawaiian rocks has been rapid. The knowledge is, of course, the accumulation of the findings of many workers, starting with the visit of J. D. Dana to the islands in 1840, as a member of the U. S. Exploring Expedition. Outstanding among recent workers are Hisashi Kuno of Tokyo University, P. Niggli of the University of Zurich, C. E. Tilley of Cambridge University, H. S. Yoder of the Geophysical Laboratory of the Carnegie Institution of Washington, and H. A. Powers of the United States Geological Survey.

During 1960 and 1961 two studies have largely confirmed, but also extended and somewhat modified, the previous petrogenic picture. In April, 1960, the junior author of this paper, on leave from the Tokyo Institute of Technology, commenced a series of chemical analyses of Hawaiian lavas at the University of Hawaii under a National Science Foundation grant to the senior author. At the end of March, 1961, approximately 150 new analyses, primarily of the hitherto largely neglected "primitive" lavas of the Hawaiian volcanoes, had been completed. These have helped fill important gaps in the basic knowledge of Hawaiian rocks. Study of them is continuing.

During July, 1960, a core hole was drilled in the crust of the recently erupted lava pool in Kilauea Iki crater of Kilauea volcano, and pene-

trated into the molten lava beneath. The results of study of the drill-hole samples and samples of the earlier lava of the eruption are reported in this paper.

Acknowledgments. The core hole in the crust of the Kilauea Iki lava pool was drilled for the Lawrence Radiation Laboratory of the University of California in cooperation with the University of Hawaii, and the chemical analyses of the core samples were done at the University of Hawaii for the Lawrence Radiation Laboratory. The entire program is a part of the Lawrence Radiation Laboratory's Plowshare Program for the development of peaceful uses of atomic energy. The results of other aspects of the investigation will be published by members of the staff of the Lawrence Radiation Laboratory.

The drilling was done by a crew in the employ of Nat Whiton of Honolulu, under the general supervision of Walter Bennett and Donald E. Rawson of the Lawrence Laboratory. General scientific supervision was furnished by Macdonald. Thanks are due to the National Park Service for permitting the drilling for scientific purposes within Hawaii National Park, and to the Lawrence Radiation Laboratory for permitting us to publish the chemical analyses and other data on the core samples.

The sample of Pele's hair analyzed was collected and given to us by Mr. H. Ikawa, of the Department of Agronomy, University of Hawaii.

Two analyses (S-1 and S-2) in Table 1 are by J. H. Scoon of Cambridge University.

We wish to express our thanks to A. T. Abbott, of the University of Hawaii, for critical reading of the manuscript.

HAWAIIAN ROCK SUITES

In the classical Mull Memoir (1924), E. B. Bailey and his associates distinguished three principal rock types, which they termed the plateau, central porphyritic, and central nonporphyritic types. In 1933, W. Q. Kennedy applied the names *olivine basalt* and *tholeiite* to the first and

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last types, respectively. In 1935, H. A. Powers recognized the presence of both these types in the Hawaiian Islands, though he did not employ the same terminology. Later Macdonald (1949a: 88) also pointed out that, although it had been thought by Kennedy to be absent from the oceanic areas, tholeiite is present in Hawaii. In 1955, Powers emphasized the essentially silica-saturated nature of the lavas of Mauna Loa and Kilauea. Although it had been anticipated to some extent by Powers (1935), C. E. Tilley (1950) was the first to definitely point out the presence of two distinct rock series in Hawaii. These he termed the *tholeiitic* and *alkali olivine basalt* series.

Tholeiite has been defined (Tilley, 1950; Kuno *et al.*, 1957) as a rock essentially saturated or slightly oversaturated with silica in which magnesian olivine bears reaction relationship to orthopyroxene and Ca-poor clinopyroxene. In contrast, alkali olivine basalt was defined as an undersaturated rock in which magnesian olivine and Ca-rich clinopyroxene undergo parallel crystallization. The characteristic groundmass pyroxene of tholeiite is pigeonitic, though the wollastonite content ranges from about 40 per cent to less than 10 per cent. That of alkali olivine basalt is Ca-rich augite. Hypersthene is present in some tholeiites.

Recently Kuno (1960) has pointed out the wide distribution of basalts resembling the central porphyritic type of Mull in their richness in alumina, but differing from it in being essentially nonporphyritic. High-alumina basalt of this type has not been found in the Hawaiian Islands, though some rocks containing abundant phenocrysts of feldspar are moderately high in alumina.

The predominant lavas of the great bulk of the visible part of the Hawaiian shield volcanoes contain scattered to moderately abundant phenocrysts of olivine, commonly as much as 5 mm. in diameter. These rocks have been called "olivine basalt" by Macdonald (1949a, b). Typically, however, the olivine phenocrysts are partly resorbed, and obviously were reacting with the remaining liquid at the time of consolidation of the rock. Chemical analyses show many of these rocks to be essentially saturated in silica, and the pyroxenes are lime-poor. They are thus typical

tholeiites. They grade into other rocks that are otherwise similar but contain normative olivine. The extreme of the latter group is picrite-basalt of oceanite type, which may contain more than 50 per cent olivine phenocrysts. These rocks are chemically undersaturated with silica, and even with the attainment of complete equilibrium on crystallization should contain modal olivine. As in the more silica-saturated types, however, phenocrystic olivine commonly has separated in excess of its stoichiometric proportion, and was undergoing reaction with the liquid at the time of consolidation, as is indicated by their partial resorption. The groundmass pyroxene is largely or entirely lime-poor augite and pigeonite. Thus, although they are undersaturated with silica and therefore not true tholeiites, these rocks conform with Tilley's definition of tholeiite as a rock in which magnesian olivine bears a reaction relationship to Ca-poor pyroxene, and the entire group from the nonporphyritic true tholeiites to the picrite-basalts of oceanite type may be termed the *tholeiitic suite*.

Both Powers (1955) and Macdonald (1944) have pointed out that the variations within the tholeiitic suite can be largely accounted for by settling of olivine phenocrysts in the magma, though movement of minor amounts of pyroxene and plagioclase also probably are involved (Muir and Tilley, 1957; Macdonald, 1949b: 1576). Locally differentiation has yielded small amounts of iron-rich basalt and granophyre (Kuno *et al.*, 1957).

The major tholeiitic part of the Hawaiian shields is succeeded by a relatively small amount of lavas of other types, including alkali olivine basalt, picrite-basalt of ankaramite type, hawaiite (Macdonald, 1960), mugearite, and trachyte. This group may be called the *alkalic suite*, because of its relationship to alkali olivine basalt, and because the great majority of the members of the group contain a larger proportion of alkalis than do members of the tholeiitic suite that contain the same amount of silica. The lavas of the alkalic suite constitute only a few per cent of the total bulk of the Hawaiian volcanic mountains. The nature of the transition from the tholeiitic to the alkalic suite will be discussed in detail in a future report describing the results of the recent chemical analyses.

A still later group of lavas, which may be called the *nephelinic suite*, consists characteristically of nepheline basalt and melilite-nepheline basalt, but includes also basanites, and alkali olivine basalts ("linosaites") in which nepheline is present in the norm though not in the mode. The nephelinic suite is in general separated from the rocks of the other groups by a profound erosional unconformity (Stearns, 1946: 22).

THEORIES OF ORIGIN OF HAWAIIAN ROCK SUITES

There appears to be little or no question that the tholeiitic magma originates in the upper part of the earth's mantle, probably at a depth of about 30 or 40 mi., and that variations within the suite are largely or entirely the result of crystal differentiation. The same degree of certainty does not extend to the alkalic suite. Macdonald has previously attributed the formation of the more alkalic members of the alkalic suite to differentiation of a parent magma corresponding approximately in composition to the average basalt of Kilauea (Macdonald, 1949a: 92; Stearns and Macdonald, 1946: 205), or to an average of basalts from all Hawaiian volcanoes (Macdonald, 1949b: 1569). The former average corresponds with tholeiite only slightly undersaturated with silica. The latter average included alkali olivine basalts, and therefore is a little higher in alkalis and less saturated with silica than the Kilauean average. Calculations indicated that the alkalic rocks could be derived from either parent by crystal differentiation. To do so, however, it was necessary to hypothesize the separation of a large amount of pyroxene (both diopside and hypersthene) from the magma. Derivation of alkali olivine basalt *per se* was not considered, because it was not recognized as an independent rock type. The possibility of other differentiation processes, such as alkali transfer by volatiles, was also recognized.

Tilley (1950: 44-45) also attributed the various members of the alkalic rock suite to crystal differentiation of tholeiite, separation of hypersthene in place of olivine producing the alkali olivine basalt. Powers (1955) agreed to the importance of the movement of olivine crystals in

producing the variations among the tholeiitic basalts, but pointed out, as indeed he had earlier (Powers, 1935), that crystal differentiation alone is inadequate to produce alkali olivine basalt from a *saturated* tholeiite.

It certainly is true that desilication of a magma by crystal differentiation can only result from the removal of crystals containing more silica than the magma. The removal of pyroxene from tholeiite can perpetuate a state of undersaturation in silica, but cannot bring it about. No mineral containing more silica than a saturated tholeiite magma is likely to form and separate except during the very latest stages of crystallization. Provided, however, that a distinctly undersaturated tholeiitic magma exists as a liquid, crystallization of pyroxene can not only perpetuate the undersaturation, but increase it. Murata (1960) has suggested that alkali olivine basalt is derived in this way from undersaturated tholeiitic magma.

Kuno *et al.* (1957: 212) agree with Powers that crystal differentiation cannot produce alkali olivine basalt from tholeiite. Instead, they assume the existence of two independent primary basalt magmas, tholeiite and alkali olivine basalt, formed by partial melting of peridotite at different levels in the mantle, incongruent melting of pyroxene at the higher level supplying extra silica for the tholeiite. More recently, Kuno (1960) has hypothesized still a third primary magma, high-alumina basalt, produced by melting in the mantle at a depth intermediate to the other two levels.

For several reasons, the existence of two primary basalt magmas in Hawaii appears improbable. Chemical analyses demonstrate a complete intergradation of the two types in composition (Figs. 1 and 3). Furthermore, it seems unlikely that melting at a deeper level in the mantle would produce a magma richer in alkalis than would melting at a shallower level. If anything, the reverse would be expected. These arguments are far from conclusive but, particularly when it is remembered that the rocks of the alkalic suite comprise only a very small proportion of the total, they do suggest that in some way alkali basalt magma is produced from tholeiitic magma, rather than having a wholly independent origin.

KILAUEA IKI LAVA

The pool of lava in Kilauea Iki crater, a pit crater immediately adjacent to the east edge of Kilauea caldera, was accumulated during the eruption that lasted from November 14 to December 20, 1959. The eruption consisted of 16 separate eruptive phases, from 2 to 167 hr. in length, separated by quiet periods of 8–101 hr. duration during which part of the lava flowed back into the vent from which it had issued (Macdonald, in press). Lava from fissures on the southwest wall of the crater about 300 ft. above the pre-eruption floor poured down the crater wall and formed a pool that gradually deepened until its surface was above the level of the original vents. Temperature measurements up to nearly 1200° C. were obtained on the lava fountain at the vent (Richter and Eaton, 1960). During eruptive phases lava was added to the crater fill partly by injection beneath the crust and partly by spreading over the previous crust. A new crust formed quickly on the molten lava as each successive outpouring covered the crater floor, but from time to time broke up and foundered during convective overturns in the liquid. The latter suggests that submerged crusts of previous eruptive phases had been largely destroyed (possibly accumulating as sunken fragments at the bottom), leaving a pool of melt that was essentially continuous from bottom to top. The final depth of the pool is approximately 380 ft.

In July, 1960, 7 months after the end of the eruption, the drill hole already mentioned was sunk into the solid crust of the lava in Kilauea Iki crater. Continuous core samples were taken, and cutting samples were preserved from successive drill runs to supplement the cores in intervals in which core recovery was poor. On July 25 the drill bit encountered very viscous semi-solid material at a depth of 19.1 ft., and at 19.5 ft. it entered underlying liquid lava and started to sink into it. The tools were immediately removed from the hole, and a sample of the liquid that had congealed in it was removed from the bit. Additional samples were taken the next day by thrusting the drill pipe, without a bit, down into the liquid and withdrawing it. By the morning of July 28 liquid lava had risen in the hole to a level 18.7 ft. below the surface.

Eight samples from the drill hole, and one of the surface crust adjacent to it, have been analyzed chemically. They are listed in Table 1. Three analyses of lava extruded earlier in the eruption also are given. Of these, one is of Pele's hair wafted from the crater during the first days of the eruption. The other two (S-1 and S-2), by J. H. Scoon of Cambridge University, represent lava poured into the crater and spatter thrown onto the crater rim during the first eruptive period, between November 14 and 21.

Analyses 9 and 10 are of samples of the liquid lava that underlay the solidified crust. It will be noted that the two are not identical. Sample 10 is decidedly richer in alkalis. Sample 9 contains many more phenocrysts of olivine than sample 10, and is presumed to have come from a slightly lower level in the liquid.

Column 1 of Table 1 is an analysis of Pele's hair formed at the beginning of the eruption. Scattered phenocrysts of olivine were present in the Pele's hair, but none were included in the sample analyzed. The sample consisted essentially wholly of glass, even microlites being almost entirely absent. Therefore, the analysis represents magma that was completely liquid at the time of eruption. The norm indicates a notable degree of undersaturation of the liquid in respect to silica. It has generally been assumed that normative olivine in tholeiitic rocks is largely the result of addition to the magma of solid crystals of olivine that have sunk from higher levels. In the case of the Pele's hair of analysis 1 the undersaturation is not, however, the result of inclusion of olivine crystals in the analyzed sample. The liquid phase of the magma was itself undersaturated. Yet its very low content of alkalis and alumina mark it clearly as a member of the tholeiitic suite. It is close to the value suggested by Bowen (1928: 164) as the limit of undersaturation in completely liquid basaltic magmas, though less undersaturated than some rocks believed by Drever (1956) to have been derived from completely liquid magmas.

In thin section the samples from the upper 17 ft. of the drill hole differ from each other almost entirely in the abundance of olivine phenocrysts, which range from about 10 per cent in the sample from 16.5 ft. to 40 per cent in that from 7.5 ft. The latter is a picrite-basalt of oceanite

TABLE 1
CHEMICAL ANALYSES OF LAVAS OF THE 1959 ERUPTION IN KILAUEA IKI

	1	2	3	4	5	6	7	8	9	10	11	S-1	S-2
SiO ₂	48.82	46.77	46.99	44.58	45.61	45.63	47.24	48.25	48.43	47.73	38.85	48.91	48.13
Al ₂ O ₃	13.42	12.04	12.14	9.25	9.06	10.58	11.14	12.90	13.00	14.58	0.31	12.42	11.62
Fe ₂ O ₃	1.70	1.72	2.55	1.27	1.85	1.85	1.41	1.78	1.32	1.36	0.55	1.34	1.27
FeO	9.90	9.95	9.19	10.76	10.49	10.26	10.22	9.88	11.25	12.99	12.21	10.23	10.40
MgO	9.00	14.85	14.33	23.46	21.48	18.41	15.66	11.39	9.39	6.01	47.69	10.96	13.78
CaO	11.32	9.89	9.90	7.18	7.79	8.40	9.56	10.38	10.03	8.92	0.00	10.44	9.64
Na ₂ O	2.25	1.53	1.51	1.10	1.28	1.31	1.53	1.75	2.10	2.43	0.00	2.20	2.04
K ₂ O	0.58	0.38	0.40	0.29	0.30	0.38	0.39	0.45	0.60	0.98	0.00	0.54	0.50
H ₂ O+	0.02	0.19	0.28	0.10	0.27	0.18	0.23	0.35	0.04	0.09	0.15	0.02	0.01
H ₂ O—	0.02	0.04	0.06	0.04	0.20	0.23	0.14	0.07	0.25	0.00	0.00	0.00	0.00
TiO ₂	2.77	2.28	2.24	1.73	1.77	2.05	2.20	2.52	2.98	3.95	0.05	2.64	2.38
P ₂ O ₅	0.24	0.24	0.25	0.19	0.16	0.16	0.15	0.28	0.32	0.43	0.00	0.25	0.23
MnO	0.18	0.18	0.18	0.18	0.17	0.18	0.16	0.18	0.18	0.20	0.16	0.15	0.18
Total	100.22	100.06	100.02	100.13	99.90	99.71	100.03	100.18	99.89	99.67*	99.97	100.10	100.18

NORMS

or	3.34	2.22	2.22	1.67	1.67	2.22	2.22	2.22	3.34	6.12	2.78	2.78
ab	18.86	13.10	12.58	9.43	11.00	11.00	13.10	14.67	17.82	20.44	18.34	17.29
an	24.74	24.74	25.30	19.18	18.07	21.96	22.24	26.13	24.19	26.13	22.80	21.13
di	12.30	9.86	9.63	6.61	8.12	7.89	10.21	9.86	9.86	6.38	22.24	20.43
		7.50	6.70	6.60	4.70	5.70	5.50	7.00	6.30	5.80			2.90
hy	4.09	2.38	2.24	1.32	1.72	1.72	2.38	2.90	3.56	3.43	16.08	12.83
		9.30	10.20	13.80	10.00	9.40	10.70	11.30	15.50	12.60			8.40
ol	5.02	3.56	4.49	2.77	2.64	3.30	3.96	7.13	7.79	10.16	10.25	18.70
		3.99	14.14	10.64	28.35	26.53	20.86	14.63	4.69	3.57			2.59
mt	2.55	5.71	3.88	8.46	8.67	7.14	6.02	2.34	2.55	3.57	1.86	5.02
		2.55	2.55	3.71	1.86	1.86	2.78	2.09	2.55	1.86			2.09
il	5.32	4.41	4.26	3.34	3.34	3.95	4.26	4.71	5.78	5.62	0.67	0.51
		0.67	0.34	0.34	0.34	0.34	0.34	0.34	0.67	0.67		

1. Pele's hair, free of olivine phenocrysts, erupted during the early stages of the eruption; collected by H. Ikawa, Nov. 22, 1959. T. Katsura, analyst.
 2. Surface of lava crust adjacent to Lawrence Radiation Laboratory drill hole. T. Katsura, analyst.
 3. Core from drill hole at depth of 4 ft. T. Katsura, analyst.
 4. Core from drill hole at depth of 7.5 ft. (picrite-basalt of oceanite type). T. Katsura, analyst.
 5. Core from drill hole at depth of 7.7 ft. (picrite-basalt of oceanite type). T. Katsura, analyst.
 6. Cuttings from drill hole in interval between 12 and 14 ft. depth. (No core was recovered.) T. Katsura, analyst.
 7. Core from drill hole at depth of 13.9 ft. T. Katsura, analyst.
 8. Core from drill hole at depth of 16.2 to 16.8 ft. T. Katsura, analyst.
 9. Liquid lava from beneath crust. T. Katsura, analyst.
 10. Liquid lava from beneath crust. T. Katsura, analyst.
 11. Olivine phenocryst from picrite-basalt at depth of 7.5 ft. in drill hole. T. Katsura, analyst.
 S-1. Olivine basalt lava poured onto floor of Kilauea Iki between November 14 and 21, 1959. J. H. Scoon, analyst. (Tilley, 1960: 494.)
 S-2. Spatter thrown onto south rim of Kilauea Iki crater between November 18 and 21, 1959. J. H. Scoon, analyst. (Tilley, 1960: 494.)

type. It is believed to be the olivine-enriched lower part of the last lava to spread across the crater floor. No phenocrysts other than olivine are present in any of the samples. The groundmass is intergranular to intersertal, and consists of calcic plagioclase, averaging about An_{65} , monoclinic pyroxene, iron ore, and locally interstitial glass. The pyroxene ranges from augite with an optic axial angle of at least 50° to pigeonite with an angle close to 0° . No silica mineral was observed. Glass increases gradually in samples below 15 ft., suggesting that interstitial fluid in the rocks was chilled at the time of sampling.

Samples 9 and 10, the congealed liquid picked up in the end of the drill pipe, are much alike except for greater abundance of olivine phenocrysts in the former. Both consist predominantly of glass. Around the edge a zone 1–2 mm. thick consists of about 85 per cent pale brown glass with scattered microlites of feldspar, pyroxene, and magnetite. This appears to have resulted from quick chilling of the liquid against the steel pipe. The rest of the core consists of black to deep brown glass, containing phenocrysts of olivine up to 1.5 mm. long, and small grains of plagioclase and pyroxene, locally clotted together in glomeroporphyritic texture. The larger olivines have $(-)\ 2V = 80^\circ \pm$. They show moderate skeletal development, and little or no signs of resorption. The larger pyroxene grains are lime-poor augite, with $(+)\ 2V = 50^\circ \pm$. Some smaller grains have $(+)\ 2V = 30^\circ \pm$. Small grains of magnetite are present, and the dark color of the glass appears to result from very finely dispersed iron ore. The proportion of glass is variable, but averages 50–60 per cent.

All but one of the Kilauea Iki samples are quite definitely tholeiitic. The single exception is sample 10, which is transitional from the tholeiitic to the alkalic rocks. In Figure 2, in which total alkali content is plotted against silica, sample 10 lies just within the alkalic

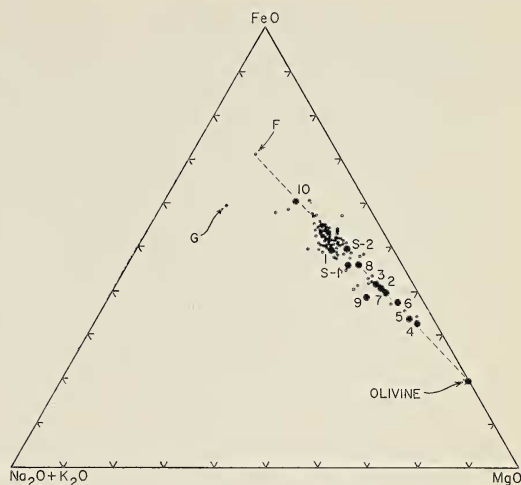


FIG. 1. Diagram of compositional variations in tholeiitic rocks of the Hawaiian Islands. Large dots represent the Kilauea Iki samples, the numbers corresponding with those in Table 1. Small dots represent other rocks. *F* represents the position of the iron-enriched segregation veinlet described by Kuno *et al.* (1957), and *G* indicates the position of the granophyre from Palolo Quarry, Honolulu, described by the same authors.

basalt field. On the basis of very quick inspection of the analyses, Dr. Kuno has suggested (oral communication, March 2, 1961) that sample 10 represents an iron- and alkali-enriched segregation similar to the veinlet from a flow in the wall of Kilauea caldera described by him and his associates (1957: 187). Indeed, in Figure 1 the point representing the iron-enriched segregation veinlet (*F*) lies directly on the trend of the Kilauea Iki rocks. However, the veinlet is distinctly poorer in alumina and richer in silica than Kilauea Iki sample 10, and lies well within the tholeiite field (Fig. 2). The similarity of Kilauea Iki sample 10 to typical alkalic basalts strongly suggests the possibility of derivation of the alkalic basalts in general from *undersaturated* tholeiitic magma.

TABLE 1 (Cont.)

* Four careful determinations of each component in analysis 10 were made. The reproducibility (precision of measurement) is sufficient for the present purpose. Cu, Zn, V, Ba, Sr, Cr, Mo, W, and Pb were detected qualitatively by means of X-ray, but not in significant amounts, and cannot therefore be responsible for the low total in this analysis. The latter is the result of an appreciable amount of graphite in the analyzed sample, which was not soluble in mixed solutions of H_2SO_4 and HF or HNO_3 and HF. The graphite unquestionably came from the powdered graphite used to lubricate the joints of the drilling tools. The amounts of F, Cl, and C are being determined at the Tokyo Institute of Technology.

TABLE 2

COMPOSITIONS OF MATERIAL OBTAINED BY CALCULATION, ASSUMING VARIOUS AMOUNTS OF OLIVINE ADDED TO A PARENT MAGMA OF THE COMPOSITION OF THE PELE'S HAIR, COMPARED WITH COMPOSITIONS OBTAINED BY ACTUAL ANALYSIS OF KILAUEA IKI DRILL-HOLE SAMPLES

	SAMPLE 2		SAMPLE 3		SAMPLE 4		SAMPLE 5		SAMPLE 6		SAMPLE 7		SAMPLE 8		SAMPLE 9	
	Anal.	Calc.	Anal.	Calc.	Anal.	Calc.	Anal.	Calc.	Anal.	Calc.	Anal.	Calc.	Anal.	Calc.	Anal.	Calc.
SiO ₂	46.8	47.4	47.0	47.5	44.6	45.1	45.6	45.5	45.6	46.4	47.2	47.1	48.3	48.3	48.4	48.8
Al ₂ O ₃	12.0	11.5	12.1	11.6	9.3	8.6	9.1	9.0	10.6	10.3	11.1	11.2	12.9	12.6	13.0	13.4
CaO.....	9.9	9.6	9.9	9.7	7.2	7.0	7.8	7.6	8.4	8.5	9.6	9.4	10.4	10.6	10.0	11.3
Na ₂ O.....	1.8	1.9	1.8	1.9	1.4	1.4	1.2	1.5	1.5	1.7	1.5	1.9	2.0	2.1	2.1	2.3
K ₂ O.....	.4	.5	.5	.5	.3	.4	.3	.4	.4	.4	.4	.5	.5	.6	.6	.6
TiO ₂	2.3	2.4	2.2	2.4	1.7	1.7	1.8	1.9	2.1	2.1	2.2	2.3	2.5	2.6	3.0	2.8
P ₂ O ₅.....	.24	.20	.25	.21	.19	.15	.16	.16	.25	.18	.15	.20	.28	.23	.32	.24
Amount of olivine added (wt. per cent)	15		14		38		33		25		17		6		—	

DIFFERENTIATION IN KILAUEA IKI LAVA

In Figure 1 the analyses of samples of Kilauea Iki lava are plotted on a standard AFM diagram, together with those of 85 other tholeiitic rocks of the Hawaiian Islands. The general tholeiitic trend of the Kilauea Iki samples is apparent.

The trends of both the Kilauea Iki rocks and of the tholeiitic rocks in general head directly toward the position of olivine (Fe_{80}) on the FeO-MgO join, and it is clear that compositional variations in the suite as a whole, including the Kilauea Iki rocks, can be accounted for largely by variations in the amount of olivine subtracted from, or added to, a parent magma with a composition lying along the same trend line.

Although movement of olivine was the main control in the differentiation, calculations indicate that minor amounts of other material also are involved. Column 2 of Table 3 shows the composition of the least amount of material that must be added to magma of the composition of the Pele's hair (Table 1, column 1) to produce a rock of the composition of the picrite-basalt from a depth of 7.5 ft. in the drill hole (Table 1, column 4). The material is preponderantly olivine, but includes also calcic plagioclase, pyroxene, and iron ore. The fact that the plagioclase is wholly anorthite indicates that some amount of material greater than the least possible actually has been added, since the first plagioclase to separate from a magma of the composition of the Pele's hair would have a more sodic composition (about An_{85}). The pyroxene also would be slightly poorer in Ca and increased in amount, but olivine would remain by far the most abundant component. Similar conclusions have been reached by Muir and Tilley (1957) regarding the 1840 picrite-basalt of Kilauea.

Similar results can be obtained by assuming a liquid phase of constant chemical composition like that of the Pele's hair and adding to it arbitrary amounts of olivine of the composition of that in the picrite-basalt (Table 1, analysis 11). Table 2 shows the results of these calculations compared to the actual compositions determined by analysis. The lower line indicates the amount of olivine added in each case, calculated on the basis of the amount of MgO and FeO in both the olivine and the Pele's hair. Since

this method of calculation of necessity results in identical values of FeO and MgO in the analyzed and calculated materials, the figures are insignificant in the present connection and are omitted from the table. Note that for the most part the calculated compositions are quite close to the actual ones, again indicating that the principal substance added during the differentiation was olivine. In the case of sample 9 the agreement is somewhat less good, especially in the CaO content, suggesting that other factors than the addition of olivine have been involved. It is impossible to calculate sample 10 on the same basis, because the amount of olivine becomes negative—that is, olivine must be removed from, not added to, the Pele's hair to yield sample 10.

The composition of the liquid phase of the magma during the beginning of the eruption is represented by the analysis of Pele's hair (Table 1, column 1). However, even at that time the bulk composition of the magma was somewhat more mafic, due to the presence of olivine phenocrysts and possibly other crystals not contained in the analyzed sample. This bulk composition is probably better represented by analyses S-1 or S-2. These in turn are less mafic than the average magma extruded later in the eruption. Richter and Eaton (1960) note a general tendency for the lava of late stages to be a little more mafic than that of the early stages. The best approximation to the composition of the "parent magma" for the suite of drill-hole samples may therefore be an average of analyses 2 and 3. This average is given in column 1 of Table 3.

Whereas samples 4 to 7 are probably cumulative types, derived by addition to the parent magma of sinking crystals, largely olivine, samples 8 to 10 are probably residual magma from which crystals have been removed. In Figure 1 they lie along the same trend, but on the other side of the parent magma (samples 2 and 3) from the cumulative types. Their position on the same trend line suggests that they have been derived largely by the same general process as the other Kilauea Iki rocks and the tholeiitic rocks in general. However, in Figure 2 samples 9 and 10 lie along a line that deviates markedly from the general tholeiitic trend. Sample 10 in

TABLE 3
PROBABLE PARENT MAGMA AND MATERIAL ADDED TO OR SUBTRACTED FROM IT TO
OBTAIN OTHER ROCKS

	1	2	3	4	5	6	7	8
SiO ₂	46.9	40.6	51.4	49.2	49.0	45.4	45.1	40.5
Al ₂ O ₃	12.9	5.0	9.1	12.9	13.2	10.7	9.2	8.0
Fe ₂ O ₃	2.1	0.9	2.5	1.8	1.7	2.8	3.8	3.5
FeO.....	9.6	11.7	1.7	8.8	9.6	6.0	6.4	8.0
MgO.....	14.6	38.1	15.7	10.0	9.3	22.7	22.6	30.5
CaO.....	9.9	3.1	17.7	12.2	11.6	11.1	11.1	7.5
Na ₂ O.....	1.5	0.0	2.0	2.2	2.2	0.7	0.7	0.0
K ₂ O.....	0.4	0.0	0.0	0.5	0.6	0.0	0.0	0.0
TiO ₂	2.3	0.6	0.0	2.3	2.6	0.6	0.6	1.5

NORMS

ne.....	.....	.....	2.6	.....	.....	.....	.....	.....
or.....	2.2	.....	.....	2.8	3.3	.....	.....	.....
ab.....	12.6	.....	12.0	19.5	18.3	5.8	5.8	.....
an.....	27.2	13.6	15.8	23.9	24.5	26.1	22.0	21.7	
di	wo.....	8.8	0.7	30.0	15.0	13.5	12.1	13.5	6.5
	en.....	6.1	0.5	25.4	9.7	8.4	9.5	10.4	5.1
	fs.....	2.0	0.1	0.7	4.2	4.2	1.2	1.6	0.7
hy	en.....	11.9	2.9	7.0	8.5	5.9	7.5	3.5
	fs.....	4.0	0.7	3.2	4.4	0.8	1.1	0.4
ol	fo.....	13.0	64.3	13.8	5.8	4.4	29.3	27.0	47.3
	fa.....	5.0	14.5	0.4	3.0	2.8	4.3	4.1	6.3
mt.....	3.0	1.4	3.7	2.6	2.6	4.2	5.6	5.1	
il.....	4.4	1.2	.....	4.4	5.0	1.2	1.2	2.9
plagioclase.....	An ₆₈	.....	An ₅₇	An ₅₅	An ₅₇	An ₅₂	An ₇₉	.....
Per cent wo in pyroxene.....	27	.....	53	38	35	41	39	40
Per cent of crystallization.....	.....	.....	50	75	90	25	50	17

1. Average of analyses 2 and 3, Table 1.
2. Least amount of material that added to Pele's hair (Table 1, analysis 1) yields the picrite-basalt (Table 1, analysis 4).
3. Least amount of material that subtracted from Pele's hair yields the composition of sample 10 (Table 1).
4. Material that subtracted from Pele's hair yields sample 10, assuming 75 per cent crystallization.
5. Material that subtracted from Pele's hair yields sample 10, assuming 90 per cent crystallization.
6. Least amount of material that subtracted from column 1 of this table yields sample 10.
7. Material that subtracted from column 1 yields sample 10, assuming 50 per cent crystallization.
8. Least amount of material that subtracted from column 1 yields sample 8 (Table 1).

particular differs greatly in alkali: silica ratio from typical tholeiitic rocks, containing half again as much alkali as rocks with the same silica content lying on the main trend line, such as sample 8.

If we assume that the liquid phase of the parent magma had the composition of the Pele's hair (Table 1, analysis 1), the composition of the material that must be removed from it by crystallization to yield magma of the composi-

tion of sample 10 can be calculated. Columns 3, 4, and 5 of Table 3 indicate the composition of the material, assuming respectively 50, 75, and 90 per cent crystallization of the parent liquid.

Column 3 appears to represent an impossible situation, because the plagioclase is considerably richer in sodium (Ab₄₃) than it should be (Ab₃₀) to have separated from the parent magma at that degree of crystallization. The same objection applies in lesser degree to

columns 4 and 5. Furthermore, if the conclusion that the pool of lava beneath the crust was largely liquid at the end of the eruption is correct, the thinness of the solid crust (less than 20 ft.) seems incompatible with degrees of crystallization of 90 or even 75 per cent. Also, in column 3 the pyroxene is considerably more calcic than would be expected to crystallize from a magma of the composition of the Pele's hair.

Columns 6 and 7 of Table 3 show the composition of material that would have to be separated from a parent magma of the average composition of analyses 2 and 3 (Table 1) to yield magma of the composition of sample 10, assuming about 25 and 50 per cent crystallization respectively. The mineral compositions indicated in the norms appear quite reasonable to have crystallized from magma of that composition. This appears to furnish further corroboration that samples 2 and 3 more nearly represent the parent magma of the drill-hole samples, and to indicate that sample 10 could have been derived from that parent wholly by crystal differentiation.

In Figure 2, as in Figure 1, samples 2 to 8 lie along a trend controlled largely by movement of olivine. The sharp divergence of samples 9 and 10 from that trend can be explained largely by the onset of more abundant crystallization of pyroxene. The position of the average tholeiitic pyroxene given by Kuno (1960: 128) is plotted on the lower boundary of Figure 2, and it will be seen that a trend line from sample 8 through samples 9 and 10 intersects the silica scale close to the pyroxene point. It will also be noted that the norms of columns 6 and 7 (Table 3) contain considerably more pyroxene than does that of column 8, which represents the material that must be separated from the same parent magma to yield sample 8. The derivation of the alkali-rich sample 10 by increased crystallization of pyroxene agrees with Murata's (1960) suggestion that crystallization of pyroxene is an important factor in the formation of the alkalic basalts.

Thus, it appears possible to derive all of the Kilauea Iki rocks by crystallization differentiation, and unquestionably this process has been of prime importance. This does not, however, prove that no other process has been involved.

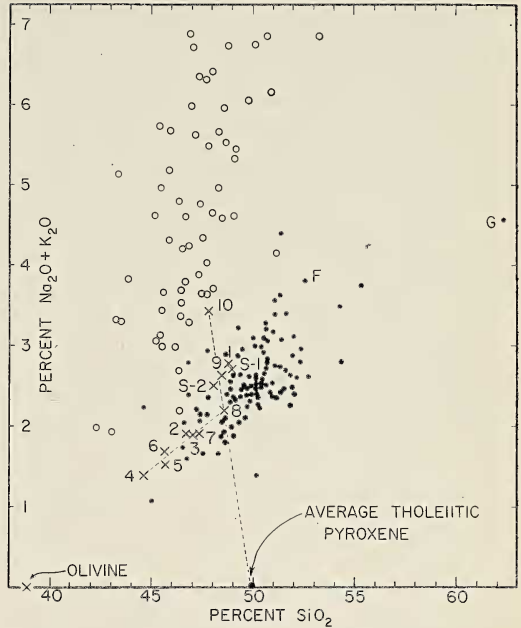


FIG. 2. Alkali : silica diagram of Hawaiian lavas. The compositions of the lavas of the 1959 eruption of Kilauea Iki are shown by crosses, those of rocks belonging to the tholeiitic suite by solid dots, and those of rocks of the alkalic suite by open circles. The point for olivine represents phenocrysts of that mineral in the 1959 lava; that for pyroxene is an average of tholeiitic pyroxenes listed by Kuno (1960: 128). The dashed line indicates the trend of differentiation of the Kilauea Iki drill-hole samples. *F* indicates the position of the iron-enriched segregation veinlet of Kilauea, and *G* that of the granophyre from Palolo Quarry (Kuno *et al.*, 1957).

Indeed, it would seem to be a foregone conclusion that other processes must have been going on in the magma and must have, to some degree, affected the composition of the magma. Such effects are most likely to have been appreciable in the rocks that depart from the main trend of differentiation, such as samples 9 and 10. The departure of these samples from the trend results principally from their greater richness in alkalis. The transfer and concentration of alkalis in one way or another as a part of magmatic differentiation has been suggested by many writers. It has thus far proved difficult to demonstrate to the satisfaction of petrologists in general, but this does not seem an adequate reason to omit it from consideration.

One of the suggested mechanisms by which alkalis may be concentrated is volatile transfer—volatile compounds moving upward toward points of gas escape, carrying alkalis in solution and releasing them because of pressure decrease at and near the top of the magma body. Another process is thermodiffusion, by which certain substances, including alkalis, migrate toward cooling surfaces (Wahl, 1946). Either or both of these may well have operated to some degree in the Kilauea Iki lava pool. Small amounts of gas have oozed from the surface of the pool constantly, ever since its formation. Likewise, the broad crusted surface of the pool exposed directly to the atmosphere and cooled by wind and frequent rains provides an ideal condition for the operation of thermodiffusion. These processes may be bringing about a gradual enrichment of the upper part of the liquid magma in alkalis. Further sampling of the congealing lava pool is highly desirable, to determine whether the trend observed in sample 10 is a continuing one.

Whether the divergence of Kilauea Iki sample 10 from the general tholeiitic trend offers a clue to the origin of the alkalic basalts cannot now be asserted. It is noteworthy, however, that it is closely similar to the transverse trend found by Tomkeieff (1937) in the Paleozoic basalts of Scotland.

CONCLUSIONS

The foregoing evidence: (1) Indicates the existence in Hawaii of completely liquid tholeiitic magma undersaturated in silica at least to the degree of containing nearly 10 per cent normative olivine; (2) confirms the dominance in the tholeiitic suite of crystal differentiation involving primarily the movement of magnesian olivine, with small amounts of pyroxene and calcic plagioclase; (3) indicates that at least marginal members of the alkalic suite can be derived from undersaturated tholeiitic magma; (4) suggests that this can be accomplished by crystallization differentiation controlled by the separation of pyroxene; but (5) leaves open the possibility of the operation of such other processes of differentiation as volatile transfer of alkalis and thermodiffusion.

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